The design and performance of the ATLAS Inner Detector trigger for Run 2 LHC Collisions at √s=13 TeV

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The design and performance of the ATLAS Inner Detector trigger for Run 2 LHC Collisions at $\sqrt{s} = 13$ TeV

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Abstract. The design and performance of the ATLAS Inner Detector trigger algorithms running online on the High Level Trigger processor farm with the LHC Run 2 data with collisions at both 50 ns and 25 ns are discussed. The HLT Inner Detector tracking algorithms are essential for the identification of nearly all physics signatures in the ATLAS trigger system. In order to deal with the expected higher rates for LHC Run 2, the Inner Detector trigger was redesigned during the 2013-15 long shutdown to satisfy the demands of the higher energy LHC operation. The detailed performance of the tracking algorithms with the Run 2 data taken in 2015 for the different trigger signatures in terms of both efficiency, and resolution is presented. The online processing times for running trigger tracking for the different trigger signatures are discussed in detail. Where appropriate, comparisons are made between the new strategies for Run 2, and the strategies adopted previously in Run 1. These comparisons demonstrate successful application and superior performance of the strategies adopted for Run 2.

1. Introduction

The LHC [1] is placed at the forefront of collision energy and intensity, allowing its associated experiments to push the boundaries of knowledge in many areas of High Energy Physics. However, these conditions provide highly demanding environments for the data-taking performed by the experiments. In particular, the trigger systems which determine whether to keep or reject collision events must cope with the high rate of collisions, while achieving accurate and efficient reconstruction of the events.

After Run 1 of the LHC between 2010 and 2013, the accelerator has been upgraded and prepared for running with higher collision energy and intensity in Run 2, which commenced data taking in June 2015. The Run 2 conditions greatly increase the demands on detector trigger systems, requiring upgrades and new approaches to be employed. A comparison of Run 1 and Run 2 conditions is shown in Table 1. In Run 1, the ATLAS Inner Detector (ID) trigger systems coped very well with the LHC running conditions, and provided excellent performance in physics reconstruction. The same performance must be kept after the upgrades and new approaches employed for Run 2.

In this document, the changes to the ATLAS ID trigger for Run 2 are discussed. The ID Trigger upgrades for Run 2 have been discussed previously [2, 3], and additional plots and information can be found there.

Table 1. Comparisons of LHC run parameters for Run 1 and Run 2.

LHC parameter	Unit	Run 1	Run 2
E_{CM}	[TeV]	7	13
Bunch separation	[ns]	50	25
Peak luminosity	[cm^{-2} s^{-1}]	7×10^{33}	2×10^{34}
Interactions per crossing (at peak luminosity)	[interactions]	≈ 21	≈ 55
ATLAS detector input rate	[MHz]	20	40

2. The ATLAS Detector, Inner Detector, and Inner Detector Trigger

The layout of the ATLAS ID is shown in Figure 1, showing the layers of silicon based pixel and SCT detectors, and straw tube based TRT detectors. The overall system is fully hermetic in the azimuthal range, and extends to a coverage of $|\eta| < 2.5$.[1] The signals registered in the ID are used to reconstruct tracks, collision vertices, and particle decay vertices through application of tracking algorithms. For Run 2 an innermost pixel system called the Insertable B Layer (IBL) [4] has been added, adding a fourth pixel barrel layer. This layer starts approximately 2 mm from the beam pipe, with the additional hits provided by the layers allowing for more robust track finding, with better impact parameter[2] resolution and therefore more precise vertex reconstruction.

The ID trigger performs track and vertex reconstruction as a part of the total ATLAS trigger system, where the reconstructed tracks and vertices will be used in further processing for the decision to accept or reject an event. As the trigger is run online[3], the ID trigger must perform the track and vertex reconstruction within tight timing constraints, whilst keeping good performance to ensure the overall trigger system accepts events of interest.

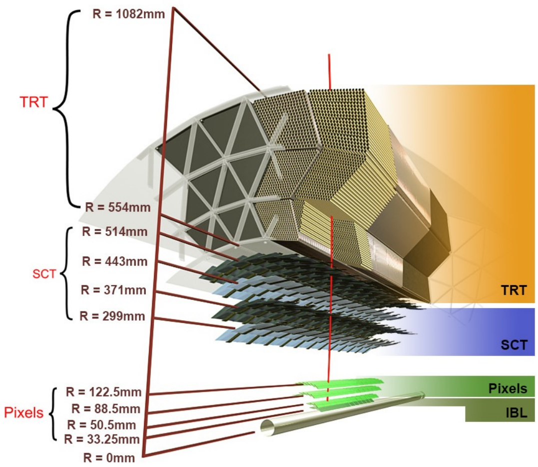


Figure 1. A sketch of a segment of the ATLAS ID barrel modules, showing the radial layout of the detection sub-systems [5]. The central grey cylinder is the LHC beam-pipe. Visible is the IBL pixel layer, which is newly added for Run 2. Not shown are the pixel, SCT, and TRT end-cap modules placed at each end of the barrel, aligned perpendicular to the beam-pipe.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

[2] The distance of closest approach of a track to some reference point.

[3] Online refers to processing done before an event has been read-out and recorded by ATLAS, while offline refers to any processing done after an event has been read-out and recorded.

3. Upgrades and New Approaches for Run 2

The most significant upgrade of the ATLAS trigger systems has been the redesign of the computational architecture. In Run 1, the trigger system consisted of a hardware-based Level 1 (L1) trigger which was followed by fast software-based Level 2 (L2) processing which used, on demand, only fragments of detector information. Finally, a software-based Event Filter (EF) stage where entire event information was available was used. The L1 trigger decision time was less than 2.5 μs; the L2 stage decision time was approximately 75 ms; and the EF stage decision time was approximately 1 s.

For Run 2, it was decided to merge the two software-based stages into a single High Level Trigger (HLT). The HLT is run from a dedicated server cluster, where each node is dedicated to processing a single event provided by L1. The merged system approach avoids repeated data preparation, access, and readout that occurred when L2 and EF were separated in Run 1. The L2 and EF track reconstruction approaches are kept by way of L2-style Fast Track Finder and EF-style precision tracking algorithms. A new hardware-based HLT pre-processor, the Fast Tracker (FTK), will be added during Run 2 [6]. The FTK will provide the HLT with tracks that are rapidly found within the full volume of the ID using template-based pattern recognition in massively parallel operation, followed by futher track fitting. The HLT tracking algorithms can then be seeded from this rough track information. Figure 2 shows a detailed overview of the ID trigger architecture in Run 2.

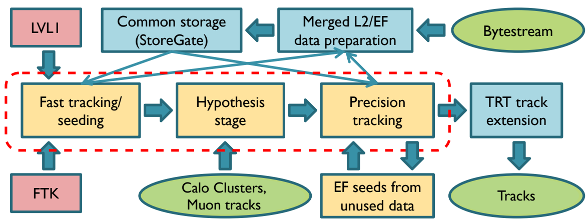


Figure 2. Detailed overview of the ID trigger architecture for Run 2 [7]. The LVL1 and FTK boxes show inputs from the respective trigger components. Bytestream refers to the binary readout of the ATLAS detector.

The new trigger architecture allows for more advanced approaches in the ID trigger track reconstruction. In particular, the merging of the L2 and EF storage allows for a multi-step approach for the reduced detector-volume Regions of Interest (RoIs) used for the tracking. In Run 1, all trigger chains used a single RoI, with the spatial extent determined by the target physics signature (for example muons). In Run 2 some trigger chains, in particular for tau triggers, have been upgraded to use two RoIs in a two-step method. In Run 1, the tracking for tau chains was run in a single RoI which was long in z and wide in η and ϕ. For Run 2, firstly an RoI which is long in z, but narrow in η and ϕ is used. The Fast Track Finder algorithm is run in this RoI, and a track of interest is chosen. A second RoI which is short in z, but wide in η and ϕ is defined around this track, and the Fast Track Finder algorithm is run again, followed by precision tracking. As such, the tracking algorithms are run in a significantly reduced volume compared to Run 1. A comparison of the Run 1 and Run 2 RoIs is shown in Figure 3, showing the positioning of the second step RoI, and the differences in volume.

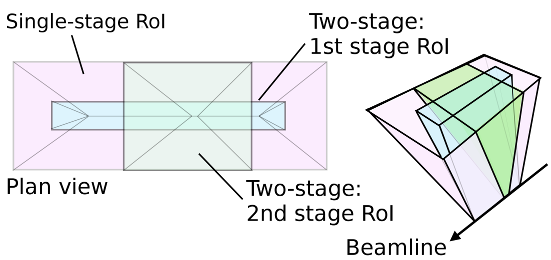


Figure 3. Sketches of the Regions of Interest (RoIs) used in tau trigger chains for Run 1 and Run 2 [8]. The single-stage Run 1 approach is compared to the two-stage Run 2 approach.

Significant improvements in algorithm timing were achieved through optimisation of the code by a number of methods. General optimisation of code 'hot spots' was achieved through use of the profiling tool `Valgrind` [9]. A much faster linear algebra library, `Eigen` [10], was used. The `Eigen` library also included automated code re-factoring. The compiler used was upgraded from `GCC 4.3` to `GCC 4.8` [11]. The code compilation was also carried out on 64-bit CPU hardware.

After all above improvements, the decision time for the entire HLT is approximately 200 ms.

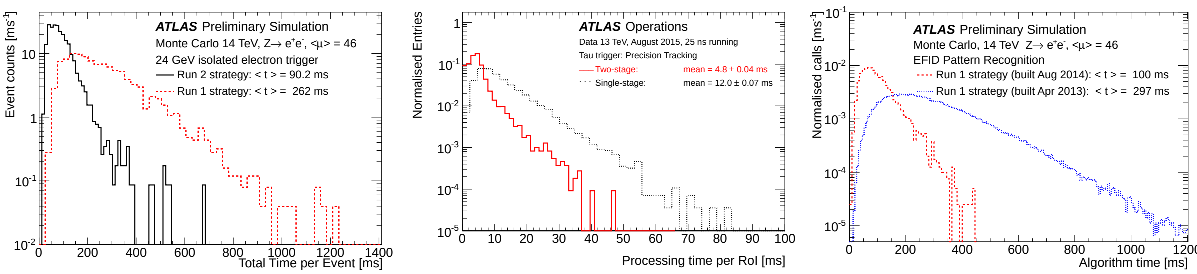
4. Results From Simulation and Run 2 Data

Figure 4 shows a number of plots that show the improvements in processing timings due to the architectural redesign, two-step RoI approach, and code optimisations mentioned in Section 3.

Figure 4(a) shows the total processing time per event for an electron trigger, comparing Run 1 and Run 2 approaches, using $\sqrt{s} = 14$ TeV Monte Carlo simulated data. Both approaches were run with the code optimisations. As such, the timing difference seen is due to the architechtural upgrades. It is seen that the mean processing time improves by approximately 65%. Total timing per event performance and improvement is similar for other physics signatures.

Figure 4(b) shows the processing time per RoI for the precision tracking in a tau trigger, comparing single-step and two-step approaches, using Run 2 $\sqrt{s} = 13$ TeV data. It is seen that the mean processing time improves by approximately 60%. The improvement for the Fast Track Finder algorithm has also been plotted, and a mean improvement of approximately 33% was seen [8]. When combining these results, the overall mean improvement is approximately 37%.

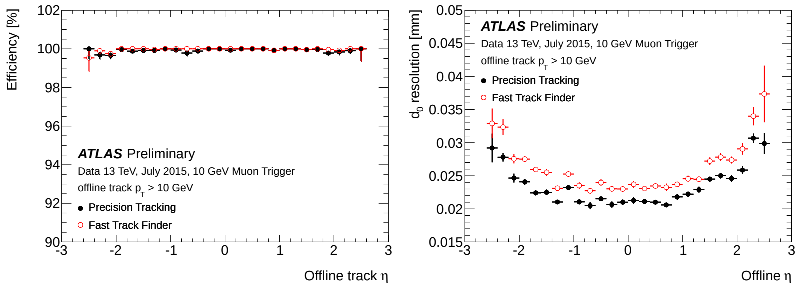
Figure 4(c) shows the processing time per algorithm-call for the pattern recognition stage of the track reconstruction, which has a notably high algorithm run time, using $\sqrt{s} = 14$ TeV Monte Carlo simulated data. The Run 1 approaches built with and without the code optimisations are compared, a mean improvement of approximately 68% is seen.



(a) (b) (c)

Figure 4. (a) Total processing time per event for a 24 GeV isolated electron trigger, comparing Run 1 (dashed red line) and Run 2 (solid black line) architectural approaches. (b) Processing time per RoI for precision tracking in a tau trigger, comparing single-step (dashed black line) and two-step (solid red line) approaches. (c) Processing time per algorithm-call for an intensive tracking algorithm, comparing Run 1 approaches before (fine dashed blue line) and after (dashed red line) code optimisations. (a) and (c) use 14 TeV $Z \to e^+e^-$ Monte Carlo simulated data, (b) uses $\sqrt{s} = 13$ TeV 25 ns bunch spacing data recorded by ATLAS in August 2015 [8].

Figure 5 shows performance for the ID trigger track reconstruction, using Run 2 $\sqrt{s} = 13$ TeV data. The performance is shown for a muon trigger, which uses a single RoI, and runs the Fast Track Finder algorithm followed by precision tracking. The track reconstruction efficiency as a function of η is shown, and it is seen that efficiency is >99% over the whole η range. Efficiency performance is similar for other physics signatures. The resolution of track transverse impact parameter, which is defined in the x-y plane with respect to the LHC beamline, is shown as a function of η, and it is seen that resolution is on the order of tens of μm and does not significantly degrade at higher η values. The efficiency and impact parameter resolution are defined with reference to muon candidate tracks found by the offline tracking algorithms, with the resolution defined as the difference between the value of the impact parameter for online and offline tracks.



(*a*) (*b*)

Figure 5. (*a*) The efficiency of tracking algorithms and (*b*) the resolution of the transverse impact parameter with respect to beamline of tracking algorithms for a 10 GeV muon trigger, as a function of offline muon candidate track η [8]. Red unfilled circles show results for the Fast Track Finder, black filled circles show results for the precision tracking. The results were produced using $\sqrt{s} = 13$ TeV 25 ns bunch spacing data recorded by ATLAS in July 2015.

5. Conclusions

LHC Run 2 has placed high demands on the ID trigger computing hardware and software used for data-taking within the ATLAS detector. Effective redesigns and new approaches have allowed it to meet these demands, and to show an excellent increase in timing performance when compared to the approaches used during Run 1. The ID trigger also continues to show excellent performance, maintaining high reconstruction efficiency and resolution. It is therefore ready to meet further expectations as conditions continue to grow more stringent as the LHC moves towards peak Run 2 running conditions. It is also well prepared for the introduction of further upgrades, particularly the introduction of the FTK in 2016.

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